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Comparative waste management options for rigid polyurethane foam waste in Thailand

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ABSTRACT

This research assesses the appropriate options for managing rigid polyurethane waste (RPUW) remaining from refrigerator/freezer dismantling in Thailand by analyzing the impacts on environment, energy and economic aspects. There are four options for RPUW management: option 1 – landfill; option 2 – incineration; option 3 – hydrolysis + landfill; and option 4 – production of lightweight concrete (LWC) mixed with RPUW (LWC-RPUW). From environmental and energy perspectives using Life cycle assessment (LCA) by Simapro software, the results showed that option 4 had the lowest human toxicity, followed by option 3, option 1 and option 2, respectively. On the other hand, option 1 had the lowest climate change and fossil depletion impacts, followed by option 2, option 3 and option 4, respectively. However, without considering energy consumption during the use phase of LWC as wall material in building, option 4 has the least energy and environmental impact. Regarding economic impact, option 4 is the only one option that can make a profit, and its net present value (NPV) is positive. In other words, it is worth refrigerator recyclers investing in a LWC-RPUW production plant. Option 4 is feasible to perform practically without subsidizing from any organization, while the other options are costly to carry out. To promote option 4, which is more appropriate considering all three kinds of impact studied here, it will be necessary to improve option 4 in terms of the insulation properties of the LWC-RPUW products to reduce the environmental impact from energy consumption during the product use phase.

1. Introduction

In the context of modern society, electrical appliances are widely used in both the household and industrial sectors. Recycling electrical appliances is a way to help create future environmental and energy sustainability (Cao et al., 2016; Dias et al., 2018; Parajuly et al., 2017). In developing countries, the major problems and drawbacks of recyclers are handling of non-valuable waste and residue from disassembly. Polyurethane (PU) is a polymeric material produced by polycondensation reaction of di-or polyisocyanate and polyol. It is used in a broad range of applications such as insulation for refrigerators/freezers, and building, cushion in furniture/mattress or automobile seats, coatings, adhesives, and sealants (Kaneyoshi, 2006). PU products are in the form of foams, with flexible and rigid types. In 2011, the PU market size in Europe, Americas and Asia-Pacific regions was about 14.2 million tons and expected to increase to 22.2 million tons by 2020 with the growth rate of 5.1% (Raimar, 2012). Focusing on Asia-Pacific (Australia, Indonesia, Malaysia, New Zealand, Philippines, Singapore, Thailand, and Vietnam), the production of PU products in 2012 accounted for 0.56 million tons and expected to increase with the annual growth rate of 6.4% because of the regulation related energy efficiency and increasing population, particularly a rising middle class (IAL Consultants, 2015). Therefore, it will be a big waste management problem after these products expire. In the recycling process of electrical appliances, rigid PU foam is residue from disassembly of refrigerators and freezers. In Thailand, the data from the Office of Industrial Economics (The Office of industrial economics, 2016) revealed that during 2007–2016, the domestic sale of household refrigerators in Thailand had increased from 1,252,000 units/year to 1,775,000 units/year. One unit of refrigerator contains approximately 5 kg of rigid polyurethane waste (RPUW) (Lv, 2009). Thus, the total amount of RPUW produced from household refrigerators was estimated to be 6300–8900 tons/year.

At present, the RPUW left over from the recycling of

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refrigerators have not been handled in a systematic manner. The RPUW management in Thailand is mostly landfill with the municipal solid waste, which requires a lot of space, due to the low density of RPUW (30–40 kg/m^3) and the high cost of transportation to landfill. However, due to landfill of RPUW requiring more space and cost for storage and transportation, some recyclers bring RPUW for outdoor combustion, resulting in environmental impact, especially air pollution. The incineration of RPUW causes the formation of highly toxic substances such as CO, NOx, HCN, Cl_2 or polybrominateddibenzodioxins and dibenzofurans (PBDD/Fs), while landfill leads to secondary pollution caused by brominated flame retardants (BFRs) leaching to the groundwater (Rittmeyer et al., 1994). In addition, disposal by incineration and landfill can cause the loss of resource use and fossil depletion because RPUW having a high specific heat capacity (6,240 kcal/kg) (Rittmeyer et al., 1994).

Increasing landfill costs, decreasing landfill space, and air pollution problems are forcing the consideration of alternative options for the disposal of RPUW. Recycling and specific valorization methods must be developed to deal with this problem. Recently, a prototype of chemical recycling for reducing the volume of RPUW has been developed by the Department of Primary Industries and Mines (DPIM). The basic principle of this method involves hydrolysis at approximately 200 °C with a pressure of 20 bars. This method can reduce the volume of RPUW by 90%, thereby facilitating and saving transportation costs for landfill (Department of primary industries and mines, 2016).

Mechanical recycling is a relatively inexpensive method, and the production process is less complicated compared to recycling with the chemical recycling method (Yang et al., 2012). When RPUWs are crushed, they are converted into low-density particles that can be used as raw material for lightweight concrete manufacture due to its thermal insulating property. The addition of the RPUWs to lightweight mortar and concrete is potentially a viable alternative for their disposal (Mounanga et al., 2008; Fraj et al., 2010; Gadea et al., 2010; Václavík et al., 2012a, 2012b, 2012c; Dvorský and Václavík, 2014). Previous studies have been dedicated to the use of RPUW in the manufacture of lightweight concrete. Mounanga et al. (2008) mixed RPUW from the destruction of insulation panels used in the building industry into cementitious mixtures in order to produce lightweight concrete (LWC). Seven concrete mixtures containing various RPUW volume fractions (13.1–33.7%) were prepared and characterized. The PU foam concrete's thermal conductivity and compressive strength were, respectively, 2–7 times and 2–17 times lower than those of the reference mixture, depending on the volume fraction of RPUW. Fraj et al. (2010) produced lightweight concretes including RPUW for the building industry as coarse aggregates (8/20 mm) with a volume fraction of 34–45%. The use of RPUW enabled the dry density of concrete compared to be reduced by 29–36% compared to that of normal weight concrete. The mechanical properties of the LWC ranged between 8 and 16 MPa for the compressive strength. Gadea et al. (2010) studied the use of RPUW from the destruction of panels used in the automotive industry into cement-based mixtures to produce lightweight mortar. Dosages were varied to replace sand with RPUW, with a volume fraction of 0–100%. Mechanical strength decreased about 50% in PU foam lightweight mortars compared to that of the normal weight mortars. Václavík et al. (2012a, 2012b, 2012c) and Dvorský and Václavík (2014) conducted experimental researches to utilize PU waste as filler for thermal insulating mortars and LWC. The physical and mechanical properties at various PU grain sizes and compositions were investigated and their suitable applications were suggested. The results of these studies show that it is technically possible to use RPUW in the manufacture of LWC. However, the RPUW used in these studies are not from refrigerators. Moreover, references regarding the assessment of the possibility of using RPUW in LWC in view of environment, energy and economic aspects (not only the technical properties), compared with alternative disposals, are scarce.

The aim of this research is thus to evaluate the benefits and impacts of the RPUW management options from environmental, energy, and economic perspectives and suggest appropriate options for Thailand. There are four management options to be considered in this research: 1) landfill, 2) incineration, 3) hydrolysis and landfill (Department of primary industries and mines, 2016), and 4) LWC production from RPUW. The paper is structured as follows: Section 2 describes the methodology of this research, including details of each management option and evaluation method. The results and discussion are presented in Section 3. In Section 4, the conclusions are presented.

2. Methodology

2.1. Waste management options

The system boundary to assess the RPUW management options of this study consists of collecting RPUW from a refrigerator recycling center in the Bangkok area, transportation, waste treatment alternatives, manufacturing and the use of commercial lightweight concrete products, as show in Fig. 1. The production of new rigid PU foam was not included in the system boundary as the new rigid PU foam has to be produced (business as usual) to use as a part of new refrigerators in all scenarios and their environmental impacts among scenarios will be offset. The waste treatment alternatives detailed below are designed for comparing their impacts. Option 1is RPUW landfill and option 2 is incineration. In these options, one ton of RPUW is transported to sanitary landfill and incineration sites located in Nakornpathom and Samutprakan Provinces, respectively, approximate 50 km from the waste generating plant, on asix-wheel truck (max load 11tons, 50% loading). Option 3 is hydrolysis and landfill. In this option, the volume of RPUW is reduced up to approximate 90% by a hydrolysis reactor, and the remaining waste is transported to a sanitary waste landfill site located in Saraburi Province, about 50 km from the waste generating plant. Option 4 is RPUW recycling as 1 m^3 of a new lightweight concrete (LWC-RPUW) product. This option explores the potential impacts of LWC mixed with RPUW as described above. The RPUW is used as a secondary material for LWC production in Bangkok. In this option, the production of LWC-RPUW would replace the production of commercial LWC in current market. As the cellular commercial LWC in Thailand is lightweight concrete mixed with polystyrene (PS) foam (LWC-PS), in options 1–3, 1 m^3 of LWC-PS is assumed to be produced in Bangkok as the baseline situation for analysis.

2.2. Evaluation of LWC-RPUW mixture and properties

In order to estimate a suitable mixture of LWC-RPUW to be used

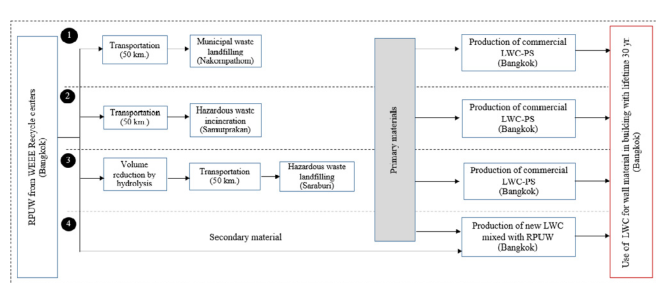


Fig. 1. The system boundary and the waste management options.

for the impact assessment, a production experiment of mixing the lightweight concrete prototype was conducted. The prototype is designed for use in non-load bearing applications. The composition of the LWC-RPUW consisted of Portland cement, sand, water and RPUW. The appropriate mixture is a mixture that its physical and thermal properties meet the Thai Industrial Standards (TIS 2601-2556; Standard of cellular lightweight concrete blocks using pre-formed foam) with the lowest raw material cost. The density of RPUW is in the range between 30 and 40 kg/m^3. The density of the rigid PU is determined by the chemicals used in its production, consisting of two main components: formulated polyols and isocyanates. In the formulated polyol, it contains all necessary additives and auxiliaries for foam production including blowing agent. Both chemicals are mixed in exact ratio and precise directions for processing developed by the chemical manufacturers to obtain the desired density of rigid PU foam. The RPUW from recycling centers was crushed by Zermar-granulator with staggered rotor blades. The foam grain with size passing through sieve No. 10 and retaining on sieve No. 40 was used as an aggregate substitute. The crushed RPUWs were used to replace sand at ratios of 0, 70, 80, 90 and 100% by volume. The operating procedure for molding the lightweight mortar consisted of mixing cement, sand and water together, followed by mixing crushed RPUW. All five mixtures used water:cement ratios of 0.5–0.6 and the ratio of sand:cement of control samples (A-0, B-0) was 3. Table 1 summarizes the mix proportions and water:cement ratios of samples. Each mix proportion was blended in a mechanical mixer and was casted in brass cubical molds with the dimension of $5 \times 5 \times 5$ cm. After casting for 24 h, the samples were removed from the molds and after curing in water for 7, 14 and 28 days, the compressive strengths were tested according to ASTM C 109 (ASTM International, 2016). The test of dry bulk density and water absorption of cured mortar at 28 days were tested according to the ASTM C 129-80 and TIS 2601-2556 (ASTM International, 2014).

2.3. Environmental and energy assessment

In order to evaluate the environmental impacts of each option, a life cycle assessment (LCA) was conducted to calculate the overall cradle-to-gate emission. LCA allows for comparisons with conventional products that may be replaced by new products, and helps to identify environmental tradeoffs. The data used for the life cycle inventory was gathered from LWC factories, literature, and databases provided in SimaPro Version 7.3. The World ReCiPe Midpoint impact assessment method (PRé Consultant, 2016) was chosen to estimate the environmental impacts in this study. The environmental impacts of RPUW mixed with LWC were assumed to be zero. To select important damage categories, eighteen impact categories according to the world ReCiPe midpoint impact of each waste management option were analyzed and sorted by SimaPro software. Three of the top five most common damage categories, consisting of climate change, human toxicity and fossil depletion, were taken into account for the assessment. Climate change is represented for the global warming potential and the unit is kg CO_2 equivalents. Human toxicity accounts for the environmental persistence (fate) and accumulation in the human food chain (exposure), and toxicity (effect) of a chemical and the unit is kg 1,4-dichlorobenzene (1,4DB). Fossil depletion is the amount of extracted fossil fuel extracted, based on the lower heating value, and the unit is kg oil equivalent (PRé Consultant, 2016).

The scope of the energy impact analysis covers energy consumption in the RPUW disposal phase and LWC production phase. The energy consumption was calculated in terms of fossil depletion, similar to the environmental impact analysis described above. Moreover, LWC is often used as a wall material in building to reduce the electrical energy consumption of air conditioning systems, due to its low thermal conductivity reducing the overall thermal transfer value (OTTV) of a building. Thus, the amount of electrical energy consumption of air conditioning systems during the use phase of a building whose opaque walls made from LWC-PS (as baseline) for options 1–3 and LWC-RPUW for option 4 were added to the energy impact analysis. The dimension of the opaque wall was assumed to be consistent with using 1 m^3 of RPUW, of which the thickness is 0.075 m and the area is 3.3 m^2. The solar heat transfer into the building was estimated as the average heat transfer through the opaque wall when it faces north, south, east and west for 24 h a day over a period of 30 years (equal to 262,800 h). The amount of electrical energy consumption used in the air conditioning system was calculated as the equation below, and the assumption values are shown in Table 2. The environmental and energy impact from this electrical energy consumption were calculated based on the emission factors of the SimaPro database, which are 0.154 kg oil$_{eq}$/kWh for fossil depletion, 0.531 kgCO$_{2eq}$/kWh for climate change and 0.344 kg 1,4DB$_{eq}$/kWh for human toxicity (PRé Consultant, 2016). The functional unit used in the LCA analysis was one ton of RPUW.

$$E = \frac{Q}{COP} \tag{1}$$

$$Q = OTTV_{ave} \times wall\ area \times operating\ time \tag{2}$$

$$OTTV_{\mathrm{ave}} = \frac{OTTV_{\mathrm{North}} + OTTV_{\mathrm{East}} + OTTV_{\mathrm{South}} + OTTV_{\mathrm{West}}}{4} \tag{3}$$

Table 1
Mix proportions of the mortar mixtures.

Series no.	Mix no.	Water:cement ratio	Sand replaced by foam (% by volume)	Mix proportions (% by weight)			
				Cement	Water	Sand	Foam
A	A-0	0.6	0	21.7	13.0	65.2	0.0
	A-70	0.6	70	39.4	23.7	35.5	1.4
	A-80	0.6	80	44.6	26.8	26.8	1.9
	A-90	0.6	90	51.4	30.8	15.4	2.4
	A-100	0.6	100	60.5	36.3	0.0	3.1
B	B-0	0.5	0	22.2	11.1	66.7	0.0
	B-70	0.5	70	41.0	20.5	36.9	1.5
	B-80	0.5	80	46.7	23.3	28.0	1.9
	B-90	0.5	90	54.1	27.1	16.2	2.5
	B-100	0.5	100	64.4	32.2	0.0	3.3

Table 2
The parameter assumptions for analysis of energy consumption during the use phase of LWC-RPUW as wall in a building (Integrated Environmental Solutions Limited, 2014; Department of Alternative Energy Development and Efficiency, 2009).

	Abbreviation	Unit	Commercial LWC	LWC-RPUW
Density	ρ	kg/m^3	650	1188
Specific heat capacity	c_p	kJ/kg•K	1.0	1.3
Thickness of LWC	Δx_{LWC}	M	0.075	0.075
Density-specific heat product	DSH	kJ/m^2•K	48.8	115.8
Equivalent temperature difference	TD_{eq}	K		
North			4.7	4.8
East			5.5	5.5
South			5.7	5.7
West			5.4	5.4
Thermal conductivity of LWC	k_{LWC}	W/m•K	0.221	0.599
Thermal resistance of air film outside building	R_o	$m^2 \bullet K/w$	0.044	
Thermal resistance of air film inside building	R_i	$m^2 \bullet K/w$	0.120	
Total thermal resistance	R_T	$m^2 \bullet K/w$	0.503	0.289
Coefficient of performance	COP		3.22	
Overall thermal transfer value	$OTTV_i$	W/m^2		
North			9.3	16.6
East			10.9	19.0
South			11.3	19.7
West			10.7	18.7
Average OTTV	$OTTV_{ave}$	W/m^2	10.5	18.5
Thermal energy transfer	Q	kWh	9171	16,044
Electrical energy input	E	kWh	2848	4983

$$OTTV_i = \frac{TD_{eq,i}}{R_{T,i}} \tag{4}$$

$$R_T = R_o + \frac{\Delta x_{LWC}}{k_{LWC}} + R_i \tag{5}$$

2.4. Economic assessment

The economic feasibility was conducted to assess the appropriateness of the waste management options in practice. The investment and expenses were estimated from the viewpoint of the refrigerator recycling centers, a source of RPUW. In option 1, the costs incurred to the recycling centers include storage area costs, costs for transporting RPUW to landfill site, and costs for landfill process. In option 2, costs include storage area costs, transportation costs, and cost for incineration process. For option 3, in addition to the costs as option 1, this option also has the costs associated with the hydrolysis process including labor cost, energy cost, raw material (water) cost, and operating area cost. The investment and operating costs of commercial LWC production is not included as they do not incur to the recycling center. For option 4, the costs include investment and operating expenses for LWC-RPUW production to increase waste value and to sell the new product to the customers. In this option, the recycling centers can obtain the income from selling LWC-RPUW. The economic return indicators used in this research are net present value (NPV), internal rate of return (IRR) and payback period (PB). Each indicator is calculated as follows:

$$NPV = \sum_{t=1}^{n} \frac{CF_t}{(1+i/100)^t} \tag{6}$$

$$0 = \sum_{t=1}^{n} \frac{CF_t}{(1+IRR/100)^t} \tag{7}$$

$$PB = T + \frac{|Cummulative\ net\ cash\ flow\ at\ the\ end\ of\ year\ T|}{Net\ cash\ flow\ in\ the\ year\ T+1} \tag{8}$$

where

CF_t = Net cash flow to project in year t (USD)
i = Discount rate (%), assumed as minimum loan rate, MLR = 6.25%
n = Project lifetime (years), 10 year
IRR = Internal rate of return (%)
PB = Payback period (year)

$$CF_t = R_t - OM_t - Inv_t \tag{9}$$

where

R_t = Income generated from management option during year t (USD), selling LWC in option 4,
Inv_t = Investment costs during year t (USD), machine and equipment cost for options 3 and 4,
OM_t = Operating and maintenance costs of waste management options during year t (USD).

The R_t is applicable for option 4, which is the income from selling LWC. The Inv_t are the machine and equipment costs for options 3 and 4. The OM_t for options 1–2 consists of 1) cost of renting space to collect RPUW before being transported to disposal (referred to as RPUW storage area cost); 2) the cost of truck rental and fuel cost for RPUW transportation (referred to as disposal transportation cost); 3) the disposal cost for landfill/incineration. The OM_t for options 3 and 4 includes additional labor cost, energy cost, material cost and operating area cost. All costs are assumed to increase annually with an inflation rate of 3% (Bank of Thailand, 2017). The system and operation assumptions for economic analysis are shown in Table 3. The amount of RPUW generated from the refrigerator recycling center in Thailand is about 15 tons of RPUW/yr.

To calculate the storage area cost, the space for storing RPUW was assumed to be equal to a six-wheel truck load capacity, which is the case with most cost-saving storage. The carry size of truck is 2.3 × 7 × 2.4 m (W x L x H) with a maximum load of 11 tons (Inter city motorway division, Department of Highways, 2005). The fuel

Table 3
The system and operation assumptions for financial cost analysis of four waste management options.

Parameter	Unit	Value			
		Option 1	Option 2	Option 3	Option 4
1. RPUW storage area cost	USD/ton of PUW	300	300	0.2	300
2. Disposal transportation cost	USD/ton of PUW	90	90	0.3	
3. Disposal cost	USD/ton of PUW	34	700	1	
4. Equipment cost	USD/unit			28,000	20,000
5. Operating cost					
5.1. Labor cost	USD/ton of PUW			9.8	51.85
5.2. Energy cost	USD/ton of PUW			504	37
5.3. Material cost	USD/ton of PUW			1.274	1750
5.4. Operating area cost	USD/yr			420	1680
6. Income	USD/yr				140,000

(diesel) consumption rate of the six-wheel truck is 0.2 L/km (Sirisenapan and Supoj, 2007), and the diesel price is 0.67 USD/L. The area rental rate and the truck rental rate were assumed to be 16.8 USD/m^2/yr (Bureau of Budget Standards, 2016) and 84 USD/round, respectively. The storage area cost, disposal transport cost and disposal cost of option 3 are lower values than those for the other options because after hydrolysis of RPUW, the volume of the residue RPUW decreases by 90% (the density of residue waste increases from 35 kg/m^3 to 1200 kg/m^3). This will result in a reduction in storage and transportation costs when computed per ton of RPUW. The machines and equipment for option 4 include foam shredder, mold, concrete mixer and wire cutting machine, with a production capacity equal to 0.2 ton of RPUW per day. The machines required for option 3 includes only the hydrolysis machine with production capacity of 1 ton of RPUW per day. To calculate the labor cost, the wage rate was assumed to be Thailand's minimum wage rate of 9.8 USD/person/day, and the working day was assumed to be 300 days/year. The number of additional workers required for options 3 and 4 is assumed to be one person, as the recycling center can utilize other available workers in the plant. The electrical loads were equal to 14,400 and 1045 MJ/ton of RPUW for options 3 and 4, respectively, and the electricity price in Thailand was equal to 0.035 USD/MJ (Metropolitan electricity authority, 2016). The raw material consumption to produce LWC-RPUW for option 4 was estimated from the experiment results obtained from Section 2.2. The material costs for option 4 include the cost of Portland cement, water and sand, which were equal to 78, 0.364 and 4 USD/ton, respectively. The material cost for option 3 is the water cost, with the water consumption equal to 3.5 m^3/ton of RPUW (Department of primary industries, 2016). The operating area for options 3 and 4 was assumed to be 25 and 100 m^2 per one set of machines. The selling price of LWC-RPUW was assumed to be equal to the market price of commercial LWC, 2800 USD/ton of RPUW.

3. Results and discussion

3.1. The appropriate mixture of LWC-RPUW

Fig. 2 shows the compressive strength and dry density of lightweight concrete mixed with RPUW. From the figure, we can see that the dry bulk density of Series A is less than that of Series B, since the w/c ratio of Series A is greater than that of Series B. The dry bulk density of the A-100 and B-100 samples were lowest, with values of 1065 and 1238 kg/m^3, respectively. The dry bulk densities of the A-100 and B-100 samples were reduced by 48% and 37%, respectively, when compared to the dry bulk density of samples without mixing RPUW (A-0, B-0). The dry bulk density of lightweight concrete blocks in accordance with TIS 2601-2556 (Thai

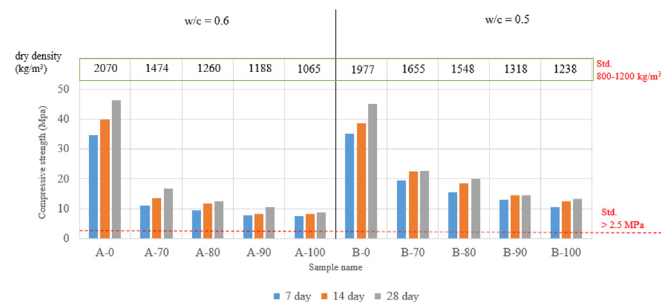


Fig. 2. Compressive strength and dry density of lightweight concrete mixed with RPUW.

Industrial Standards Institute, 2013) should be between 800 and 1200 kg/m^3 for class C10[1] and the densities of only samples A-90 and A-100 are consistent with this standard. The compressive strengths of the samples tend to decrease with increasing RPUW in samples because the proportion of sand that induces strength is reduced. The 28-day compressive strength of the A-100 and B-100 samples were lowest, with values of 9 and 13 MPa, respectively, which is in accordance with the minimum compressive strength (2.5 MPa) specified in the standard of TIS 2601-2556 (Thai Industrial Standards Institute, 2013). In addition to the criteria for compressive strength and density, TIS 2601-2556 also sets the water absorption of lightweight concrete by no more than 23% by weight; the A-90 and A-100 samples had water absorption equal to 13%, which is in accordance with the standard. From the dry bulk density, the compressive strength and water absorption properties were determined for each sample: both the A-90 and A-100 samples met the TIS 2601-2556 criteria, but the A-90 sample had a lower cement proportion than A-100. Cement is the major cost of the raw material for LWC, thus making the raw material cost for the A-90 sample lower than the A-100 sample. Therefore, the mixture of A-90 was selected to use for impact assessment later in the study.

To assess the energy consumption during the use phase of LWC as a building wall in the later section of the study, the thermal conductivity of LWC-RPUW was also tested (Fig. 3). The thermal conductivity of the samples tended to decrease with the increasing amount of RPUW mixed in the samples or tended to decrease with the decreasing sample density. The results have confirmed that the lower density translates to lower thermal conductivity, which is in line with the findings from other researchers. The thermal conductivity of the A-90 and A-100 samples were 0.599 and 0.477 W/

[1] The class of cellular lightweight concrete according to the Thailand industrial standard, which has following properties: density of 901–1000 kg/m^3, compressive strength >2.5 MPa, and water absorption <23% by mass.

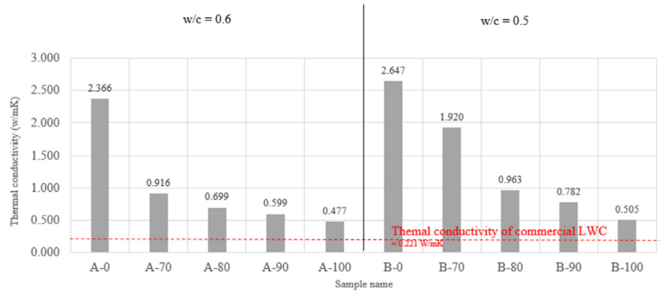


Fig. 3. Thermal conductivity of lightweight concrete mixed with RPUW.

mK, which is close to that of MdAzreeOthumanMydin, which gave a thermal conductivity of the foamcrete with a density of 1200 kg/m^3 equal to 0.39 W/mK (Mydin, 2011). However, the thermal conductivity of LWC-RPUW (A-90) is higher than the thermal conductivity of commercial LWC, equal to 0.221 W/m K, or about 170%. This is because foam used as filler in commercial LWC-PS has closed-cell structure. Normally, the cell structure of RPUW from refrigerators is closed-cell structure. However, after RPUW is crushed by granulator, its closed-cell structure is destroyed and changed to open-cell structure which has higher thermal conductivity. Consequently, the thermal conductivity of the RPUW-LWC (A-90) in this study is higher than that of commercial LWC. Fig. 4 shows SEM (Hitachi SU8030) micrographs of RPUW cell structures before and after crushing.

3.2. Environmental and energy impacts

From the calculation results of the SimaPro program, Fig. 5 shows the environmental and energy impacts of four waste management options for RPUW. Each waste management option consists of four main processes: transportation, disposal, LWC production and LWC use phase. When considering the impact of human toxicity, option 2 is the most influential option, with values of 153,928 kg 1,4DB$_{eq}$, followed by option 1, option 3 and option 4, with values of this impact being only 148,198, 135,634 and 92,290 kg 1,4DB$_{eq}$, respectively. The human toxicity impact of options 2 and 1 in the disposal process is largely due to the emission of barium and selenium, which are the main components of RPUW. Usually, barium sulfate (Barytes) is used as a filler for flexible foams and semi-rigid foams, especially for sound-absorbance (Woods, 1987). Selenium compounds act as accelerators to convert polymers into more durable materials by forming crosslinks between individual polymer chains (Msc, 1994). In the case of option 1, the emissions come from short-term leachate treatment and incineration of resulting sludge, and they also come from long-term leachates directly from municipal solid waste landfill and indirectly via incineration of sludge from leachate treatment. In the case of option 2, emissions come from long-term emissions from landfill of incineration residues into rivers and groundwater.

When considering the impacts of fossil depletion and climate change, option 4 has the highest climate change and fossil depletion impacts, followed by options 3, 2 and 1, respectively. This is mainly because the electrical energy consumption of option 4 during the operation of building, which is assumed to install LWC-RPUW as a wall, is higher than the energy consumption of other options that use commercial LWC-PS instead. Fig. 3 shows that the thermal conductivity of LWC-RPUW is higher than that of commercial LWC-PS, and this causes the electrical energy consumption for the air conditioning system of option 4 to be higher (11,506 kg oil$_{eq}$ or about 75%) than that of the other options. Option 3 has high climate change and fossil depletion impacts due to the disposal

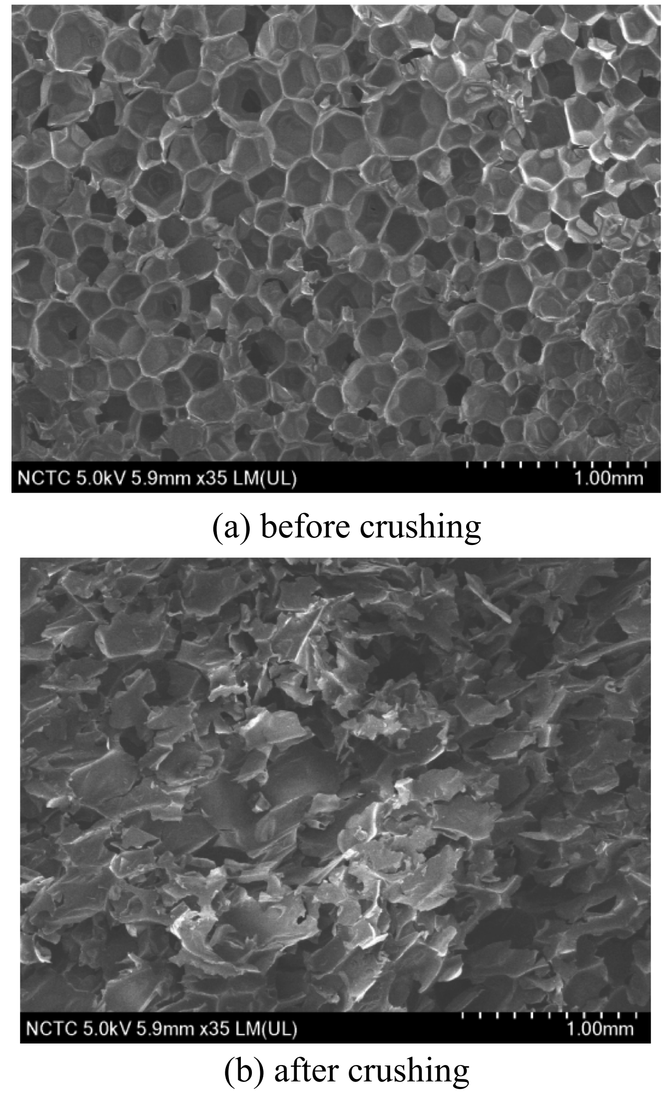
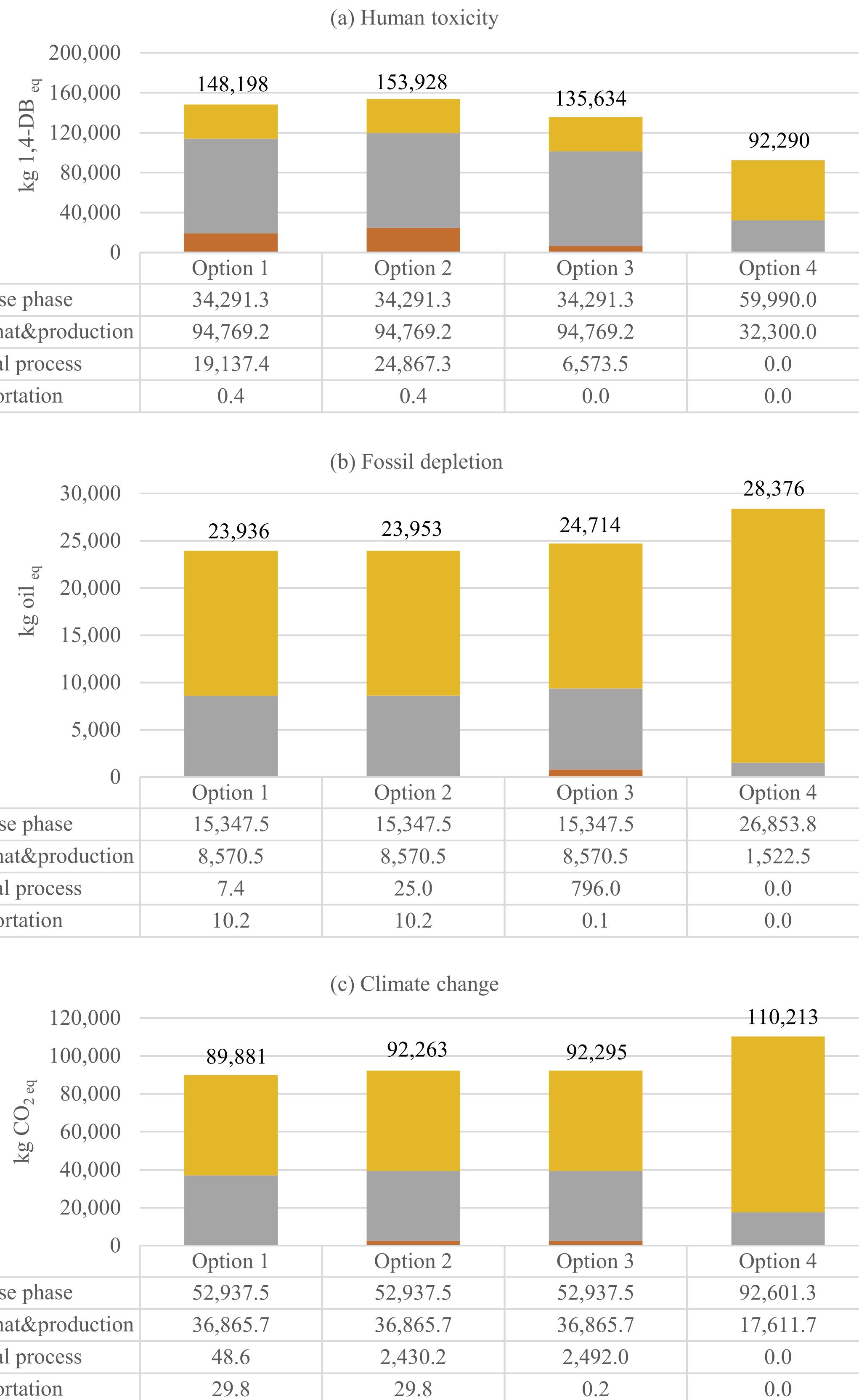


Fig. 4. SEM (Hitachi SU8030) micrographs of RPUW cell structures.

process, which uses a lot of electricity for the hydrolysis reaction by which PU can be broken down to constituent monomers or smaller components. Electricity is produced by the burning of fossil fuels, which is the main cause of CO_2 emissions and the consequent climate change effects. The climate change impact of option 1 is less than option 2, about 26%, and the pollutants in option 1, mainly from carbon dioxide and methane, are from direct release or incineration of landfill biogas. The climate change impact of option 2 is as high as that for option 3 of about 92,263 kg CO_{2eq}. The major pollutants of option 2 are from carbon dioxide, which is generated from the combustion of fossil fuels, natural gas and RPUW, burned in industrial furnace.

However, without considering the energy consumption during the LWC use phase, option 4 has the least environmental and energy impact, with impacts on climate change, fossil depletion and human toxicity equal to 17,612 kg CO_{2eq}, 1523 kg oil$_{eq}$ and 32,300 kg 1,4DB$_{eq}$, respectively. This implies that improving the insulation properties of LWC-RPUW can reduce the environmental and energy impacts of option 4.

Fig. 6 shows the comparison of the environmental and energy impacts between LWC-PS and LWC-RPUW products (option 4) to illustrate the hot spot of raw materials and energy used in LWC



(a) Human toxicity

	Option 1	Option 2	Option 3	Option 4
LWC use phase	34,291.3	34,291.3	34,291.3	59,990.0
LWC mat&production	94,769.2	94,769.2	94,769.2	32,300.0
Disposal process	19,137.4	24,867.3	6,573.5	0.0
Transportation	0.4	0.4	0.0	0.0

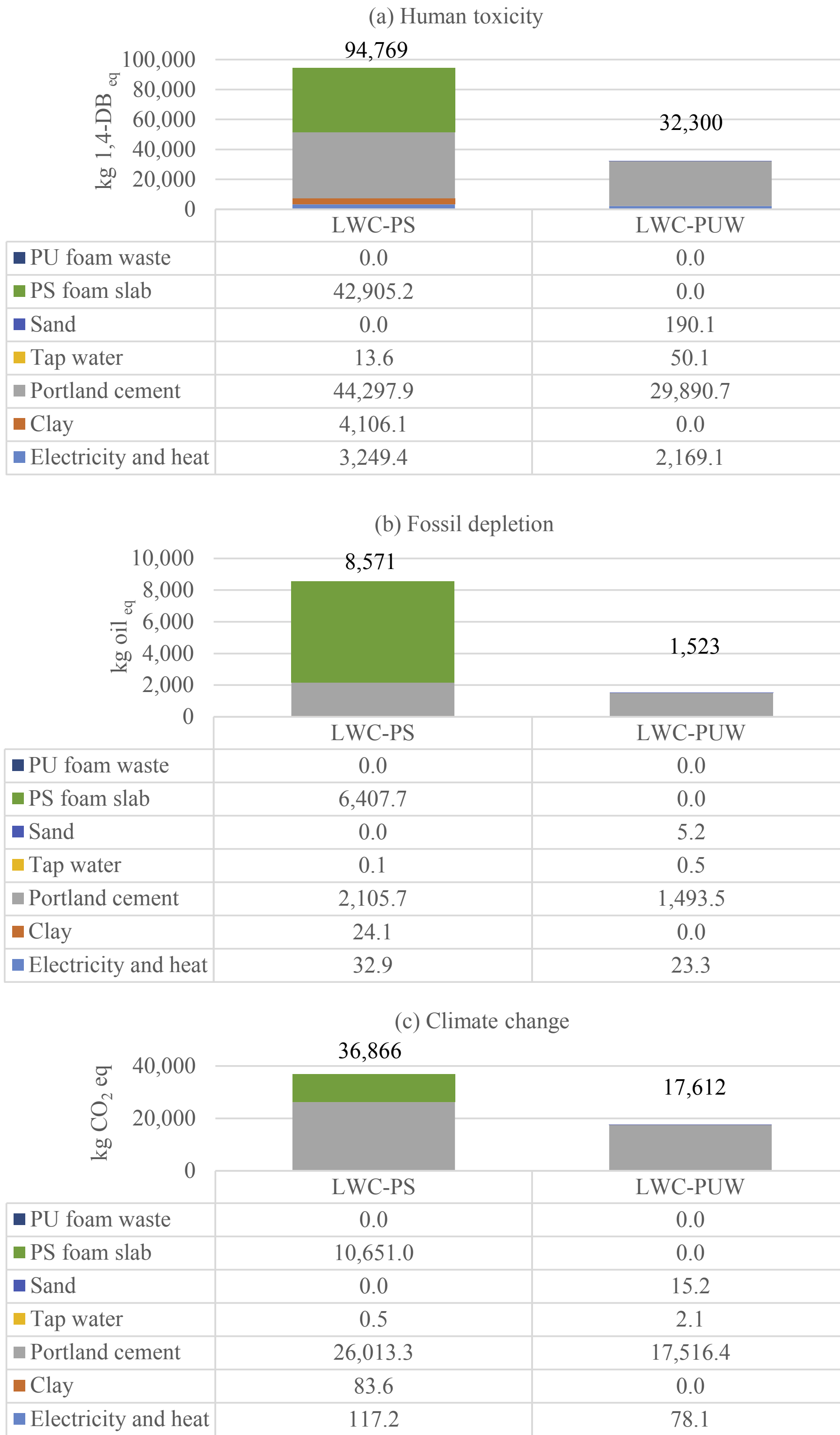
(b) Fossil depletion

	Option 1	Option 2	Option 3	Option 4
LWC use phase	15,347.5	15,347.5	15,347.5	26,853.8
LWC mat&production	8,570.5	8,570.5	8,570.5	1,522.5
Disposal process	7.4	25.0	796.0	0.0
Transportation	10.2	10.2	0.1	0.0

(c) Climate change

	Option 1	Option 2	Option 3	Option 4
LWC use phase	52,937.5	52,937.5	52,937.5	92,601.3
LWC mat&production	36,865.7	36,865.7	36,865.7	17,611.7
Disposal process	48.6	2,430.2	2,492.0	0.0
Transportation	29.8	29.8	0.2	0.0

Fig. 5. Environmental impacts of four waste management options for RPUW from refrigerator/freezers with functional unit as 1 ton of RPUW.



(a) Human toxicity

	LWC-PS	LWC-PUW
PU foam waste	0.0	0.0
PS foam slab	42,905.2	0.0
Sand	0.0	190.1
Tap water	13.6	50.1
Portland cement	44,297.9	29,890.7
Clay	4,106.1	0.0
Electricity and heat	3,249.4	2,169.1

(b) Fossil depletion

	LWC-PS	LWC-PUW
PU foam waste	0.0	0.0
PS foam slab	6,407.7	0.0
Sand	0.0	5.2
Tap water	0.1	0.5
Portland cement	2,105.7	1,493.5
Clay	24.1	0.0
Electricity and heat	32.9	23.3

(c) Climate change

	LWC-PS	LWC-PUW
PU foam waste	0.0	0.0
PS foam slab	10,651.0	0.0
Sand	0.0	15.2
Tap water	0.5	2.1
Portland cement	26,013.3	17,516.4
Clay	83.6	0.0
Electricity and heat	117.2	78.1

Fig. 6. Environmental impacts of commercial LWC-PS and LWC-RPUW with functional unit as 1 ton of RPUW.

production. It was found that the LWC-RPUW has a lower environmental impact of all three impact categories. The climate change and fossil depletion impact of LWC-PS mainly comes from Portland cement and PS foam slabs, but the impact of LWC-RPUW mainly comes from only Portland cement (assuming zero impact for RPUW, as it is recycled from refrigerators and freezers). To produce Portland cement, high temperatures of up to 1400 °C are required, thus the high amount of fossil fuel is combusted and generates high CO_2 emissions. The PS foam slab requires steam to expand the volume of expandable PS beads and the steam itself is produced in boilers mainly using natural gas as fuel (The BPF EPS Group, 2017). This combustion of fossil fuels results in higher climate change and fossil depletion impacts.

Considering the human toxicity impact, the impact of LWC-

RPUW was about half the impact of LWC-PS, with values of 32,300 and 94,769 kg 1,4DB_{eq}, respectively. Portland cement and PS foam slab are the main contributors to the human toxicity impact, because during the life cycle of the Portland cement and PS foam slab, it releases selenium and manganese to water sources at the disposal process of sulfidic tailings, spoil from lignite and coal mining.

3.3. Economic feasibility analysis

This section describes the results of the economic feasibility analysis of management options for RPUW, which is left over from disassembly of refrigerators/freezers of small recycling centers, with foam scraps of about 15 ton/yr (calculated from the 3000 refrigerator units/yr and RPUW = 5 kg/unit). The NPV, IRR and PB of four waste management options are shown in Table 4. There are no IRR and PB values for options 1–3 because in these options, investors must pay for RPUW disposal without a benefit return for the entire 10-year period, while option 4 is an alternative that has revenue from selling LWC-RPUW. Fig. 7 shows that the NPV of option 1 has the smallest negative value in comparison to options 2 and 3. It can be concluded that the RPUW management by landfill costs less than management by incineration and hydrolysis + landfill of 2.6 and 2.0 times, respectively. The result is consistent with prior studies showing that landfilling is the lowest cost waste treatment process for many types of wastes such as carbon fibre reinforced polymers (Li et al., 2016; Dong et al., 2018) and municipal waste (Reich, 2005). The maximum cost portion of option 1 comes from the RPUW storage area cost, which is approximately 51%, followed by the transportation cost and disposal costs, which are 35% and 13%, respectively. The maximum costs of options 2 and 3 come from the disposal and energy costs, accounting for 75% and 68% of the total costs, respectively. Thailand has few incinerators, while the number of landfill sites is much higher, resulting in higher disposal cost by incineration than by landfill. Consequently, without additional regulation imposed, landfill would continue to be the dominant economic choice in RPUW waste management. On the other hand, option 4 is an alternative with a positive NPV value of 21,072 USD, indicating that the investment is cost effective. The major cost of option 4 is derived from the material cost, especially the cement cost, which is 93% of the total operating cost. The IRR of the project is 35%, which is more than the MLR of 6.25%, indicating that the project investment is economically feasible. The payback period of the project is approximately 2 years, which is less than the 10-year life of the machine, indicating that the project has an acceptable level of risk. This option has a positive NPV because RPUW is transformed to a marketable and value-added product. There are other means being able to transform RPUW into value-added product. In Korea, RPUW is transformed to solid refuse fuel that can reduce disposal costs with payback period of 3 years and 8 months assuming no additional expenses and 7 years and 7 months with operating expenses included (Park et al., 2017).

As a result of the economic feasibility analysis, option 4 or the production of lightweight concrete mixed with RPUW is economically viable and might be considered as a practical method for managing RPUW without any other financial supports or subsidies from the government.

Table 4
Summary of NPV, IRR and PB of four RPUW waste management options.

Parameter	Option 1	Option 2	Option 3	Option 4
NPV (USD)	−32,611	−117,121	−97,101	21,072
IRR (%)	NA	NA	NA	35%
PB (yr)	NA	NA	NA	2.04

3.4. Policy implication

Based on the three-dimensional analysis, this research suggests option 4 as an appropriate alternative to manage RPUW in Thailand for recyclers. However, some issues need to be considered to promote and stimulate the implementation.

3.4.1. Technology aspect

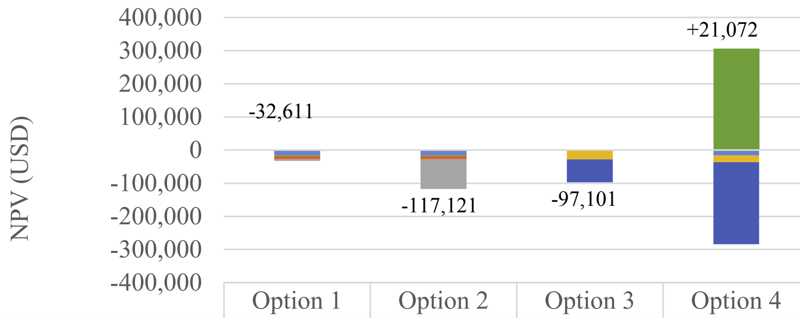
Technology regarding LWC-RPUW production should be transferred to privates and related business entities by governmental institutions to move this management option toward efficient implementation. In addition, to make option 4 more appropriate for all three aspects (economic, environment and energy), further research and development to improve thermal conductivity of LWC-RPUW should be conducted to reduce the energy and environmental impacts during the use phase of the LWC-RPUW.

3.4.2. Financial aspect

Although option 4 is economically feasible, the initial investment cost for LWC production might be the important barriers for recycling centers to implement. In order to promote the implementation, a loan with a suitable interest rate can financially support the up-front payment and potentially increase the return on investment for the recycling centers. Additionally, centralized manufacturing strategy may further improve the return of the project due to benefit from raw material collection and economies of scale. On the other hand, financial disincentive can encourage the diversion of waste from undesired alternative waste management processes; for example, the landfill tax scheme in the UK has been highly successful in diverting waste from landfill (Talbot, 2014; Li et al., 2016; EC, 2012).

3.4.3. Regulatory aspect

Thailand has drafted the act on the management of electronic waste based on the extended producer responsibility (EPR) principle since 2004, however, now it is still awaiting approval (Pollution Control Department, 2016). If the act is enacted, it will create the system allowing consumers to send back electrical equipments (take-back system) to the electronic waste recycling centers efficiently. As a result, non-valuable parts such as RPUW can be separated from municipal solid waste and easy to be managed further. The draft act also promotes the reuse of materials by special tax or fee rates for manufacturers. This measure will encourage the recycle of RPUW as the mixture of lightweight concrete block. The EPR principle has already been implemented in many countries such as Germany (Walther et al., 2010), Switzerland (Duygan and Meylan, 2015), Japan (Chung and Suzuki, 2008), Korea (Park et al., 2017), China (Zhu et al., 2012; Yu et al., 2014), and India (Pathak et al., 2017). In addition, promotion of green building can also stimulate the use of recycle material in building construction. In Thailand, assessment criteria called Thailand's Energy Rating and Sustainability (TREES) (Thai Green Building Institute, 2013) has been used as a green building certification. There are several issues to consider, one of which is about material and resources for construction phase. The criteria focus on the environmental impact reduction by the use of recycled building materials instead of virgin materials. Simultaneous promotion of green building will stimulate the designers and builders' demand for recycled materials such as LWC-RPUW. As a result, the market demand for this product can be increased.



	Option 1	Option 2	Option 3	Option 4
Income	0	0	0	305,495
Operating cost	0	0	-68,911	-247,547
Equipment cost	0	0	-28,000	-20,000
Disposal cost	-4,314	-88,824	-127	0
Disposal transportation cost	-11,420	-11,420	-38	0
PUW storage area cost	-16,877	-16,877	-25	-16,877

Fig. 7. Detail of net present value (NPV) of four RPUW waste management options.

4. Conclusion

This research assessed appropriate options for managing rigid polyurethane waste (RPUW) remaining from refrigerator/freezer dismantling in Thailand. There are four options to be considered, consisting of 1) landfill, 2) incineration, 3) hydrolysis + landfill, and 4) lightweight concrete (LWC) mixed with RPUW (LWC-RPUW). The assessment was conducted from environmental, energy, and economic perspectives. In the environmental and energy perspectives, a Life cycle assessment (LCA) was conducted to calculate the overall cradle-to-gate emission considering three damage categories, consisting of climate change, human toxicity and fossil depletion. The results showed that option 4 had the lowest human toxicity, followed by option 3, option 1 and option 2, respectively. For climate change and fossil depletion impacts, when taking into account energy consumption during the use phase of the LWC as a wall material in building, option 1 had the lowest values, followed by option 2, option 3 and option 4, respectively. However, without considering energy consumption during the use phase, option 4 gives less impact on climate change, fossil depletion and human toxicity than the other options. In the economic perspective, indicators used to assess the economic effectiveness of the management options are net present value (NPV), internal rate of return (IRR), and payback period (PB). The result showed that only option 4 is economically feasible, with a positive NPV of 21,072 USD, a project IRR of 35%, and a PB of 2.04 years, which is less than the expected technical lifetime of the machine, indicating that the project has an acceptable level of risk. This implies that option 4 can be considered a practical and effective method for managing RPUW without any other support or subsidies from the government. Thus, based on the three-dimensional analysis, this research suggests option 4 as an appropriate alternative to manage RPUW in Thailand for recyclers.

In order to move towards efficient implementation, technological, financial and regulatory issues need to be considered. In technology aspect, technology transfer to privates should be performed by governmental institutions, and research and development to further improve thermal resistivity of LWC-RPUW should be conducted to reduce the energy and environmental impacts during the use phase of the LWC-RPUW. In financial aspect, a loan with a suitable interest rate can support the up-front costs of the LWC-RPUW production. In regulatory aspect, enforcement of laws regarding electronic waste management can support separate non-valuable parts such as RPUW from municipal solid waste efficiently and encourage the recycle of RPUW as the mixture of lightweight concrete block. In addition, promotion of green building can also stimulate the use of recycle materials in building construction, resulting in increased market demand for this product.

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